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Practical X-Ray Source**

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Transition Radiation as a Practical X-Ray Source

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ABSTRACT

Transition radiation is generated when an energetic electron crosses the boundary between two different media. Theoretical calculations predict soft x-ray spectra and angular distributions that agree with experimental results. Further, recent advances in microstructure technology create the possibility of designing transition-radiation sources for several practical applications. For example, calculations indicate that a stack of 60 1 μ m-thick beryllium foils exposed to a beam of 100 MeV electrons will produce about 120 Joules of 1-2 keV x-rays per Coulomb of incident charge. The highest intensity sources appear to be bright enough for application to microlithography.

INTRODUCTION

Transition radiation (TR) is generated when an energetic electron crosses the boundary between two-different dielectric media.¹⁻³ The radiation has a broad spectrum and can extend from microwave to x-ray frequencies with substantial intensities. Photons are generated in both the forward and backward directions; but for relativistic electron energies, most of the radiation is generated in forward direction. This is schematically illustrated in Figure 1.

The properties of TR described above are very general. When used as an x-ray source for a particular application, it is possible to emphasize spectral features aspects of TR. The purpose of this paper is to demonstrate the design of a transition radiation source for production of a beam of "soft" x-rays with energies between 1 and 2 keV and with intensities which have potential application to x-ray microlithography.

SOURCE DESIGN

Since it is generated at media interfaces, transition radiation intensity will increase with the number of interfaces that a target incorporates. One simple way to create a source with a number of interfaces is to use a stack of thin, vacuum-spaced foils. However, two conditions limit the maximum number of foils which can be used to increase the emission intensity of a TR source designed for a specific spectral region.

The first condition is that the total material thickness of a stack of foils should not be much greater than the photon absorption length of the material in the spectral region of interest. If the total thickness of the source exceeds this limit, then photons generated at the upstream interfaces will nearly all be absorbed before they escape the stack.

The second condition is that for a given incident electron energy and desired photon energy, there is a minimum thickness of material required for efficient TR generation. This minimum thickness is called the formation length.³ The formation length is determined by the electron energy, photon energy and material properties. Thus, the number of foils which can be effectively used in a TR source is roughly equal to the quotient of the absorption length divided by the formation length. This behavior will be evident in calculations that will be discussed in a later section.

For specific applications, it is also desirable to configure a TR source so that its spectral intensity is maximized at a given photon energy. With currently available x-ray microlithographic photoresists, x-ray sources should have peak intensity for x-rays between 1 and 2 keV.^{4,5} This energy range allows high spatial resolution and at the same time minimizes the x-ray penetration depth into the substrate of interest.

For a single interface, the angular-integrated TR spectrum is approximately given by:⁶

$$\frac{dN}{d\omega} \sim \frac{2\alpha}{\pi} \left(\frac{1}{\omega} \right) \ln \left(\frac{\gamma\omega_p}{\omega} \right), \quad (1)$$

where $\alpha = 1/137$ is the fine structure constant ω is the photon energy, γ is the total electron energy divided by its rest energy and ω_p is the electron

plasma frequency of the material. Thus, the radiation is broadband with a $1/\omega$ frequency distribution which decreases for frequencies greater than $\gamma\omega_p$.

However, for a stack of foils the spectrum described in Equation (1) will be modified by the x-ray absorption characteristics of the foil material. In the soft x-ray range, the x-ray absorption length decreases rapidly as the photon energy decreases. When the x-ray absorption spectral variation is combined with the basic spectrum in Equation (1), the net spectrum will often show a broad peak centered in the soft x-ray energy range. As the number of foils is increased the spectral peak will shift to higher energies, because the softer x-ray energies will be more strongly absorbed. This behavior also will be evident in the calculations discussed below.

Finally, the usefulness of a TR source will depend on the angular distribution of the x-rays. For relativistic electron energies, the photon beam is emitted with a conical angular distribution with peak intensity at a half-angle of $1/\gamma$. For a single electron, the on-axis intensity is zero; but for real beams with finite radii, there is some on-axis photon intensity.

Design of a TR source optimizes photon generation in a specific energy region through the choice of parameters which specify the physical characteristics of the source. For a given electron energy, the parameters which can be varied include the two dielectric media, the material thicknesses, and the number of foils or layers in the source.

Computer calculations using theory of TR have demonstrated excellent agreement with experimental measurements for a variety of experimental conditions.³⁻⁷ The theoretical description of TR generation for the sources described below takes the form:⁷

$$\frac{d^2N}{d\Omega d\omega} = F_1 \cdot F_2 \cdot F_3, \quad (2)$$

where F_1 describes TR from a single interface in a stack of foils, F_2 describes the coherent sum of photons generated at the two surfaces of a single foil, and F_3 describes the summation of photon intensities from the stack of individual foils. For the designs considered here, these functions can be written in the forms:^{3,6-8}

$$F_1 = \left(\frac{\omega \sin^2 \theta}{16\pi^2 c^2} \right) (Z_1 - Z_2)^2 \quad (3)$$

where θ is the photon propagation angle, and Z_i is the formation length in each material and is given by:

$$Z_i = 4 \left(\frac{c\beta}{\omega} \right) \left[(1/\gamma)^2 + (\omega_p/\omega)^2 + \theta^2 \right]^{-1}, \quad (4)$$

where β is v/c , ω_p is the electron plasma frequency, when the dielectric constant of the medium is approximated by $\epsilon_1 \approx 1 - (\omega_p/\omega)^2$.

$$F_2 = 4 \sin^2(\lambda_1/Z_1), \quad (5)$$

where λ_1 is the thickness of the foil.

$$F_3 = \frac{1 - \exp(-M\sigma)}{\sigma}, \quad (6)$$

where M is the number of foils, $\sigma = \mu_1 \lambda_1$, and μ is the x-ray absorption length of the foil material.

CALCULATIONS

As an example of one possible application, equations 2-6 were used to design a TR x-ray source for microlithography. Here, the x-ray emission characteristics of a stack of beryllium (Be) foil stacks exposed to a beam of medium energy (50-200 MeV) electrons were calculated.

Figure 2 shows the angular integrated x-ray spectrum generated by stacks of 30, 60 and 120 $1\mu\text{m}$ Be foils exposed to 100 MeV electrons. The x-ray spectrum is seen to vary with the number of foils in the stack. As the number of foils increases, the spectrum is hardened by x-ray absorption. However, for 60 $1\mu\text{m}$ thick foils, the spectral peak is centered in the 1-2 keV region of interest.

Figure 3 shows the angular-integrated spectrum emitted by stacks of 60 foils with thicknesses of either 0.5, 1.0, or 2.0 μm . Although the number of transition interfaces is the same for each stack, the x-ray spectrum and intensity vary with foil thickness. The 0.5 μm foils generate the lowest intensity because this thickness is less than the approximately $1\mu\text{m}$ formation length. Again, the $1\mu\text{m}$ -foil spectrum peaks in the middle of the 1-2 keV region. And the 2 μm -thick foils generate more x-rays, but at the expense of a harder spectrum.

Figure 4 shows the calculated angular distribution of emitted x-rays vs. thickness of the foils. Here, the emission has been spectrally integrated from 1 to 2 keV. Most of the x-ray energy propagates in a narrow, forward-directed cone. The intensity peaks approximately at the $1/\gamma$ angle of 5 mr. Again, the 1 and 2 μm -thick foils generate the highest intensities.

The total 1-2 keV x-ray output vs. incident electron energy is shown in Figure 5. Here, emissions are compared for stacks with different foil thicknesses. Again, the 1 and 2 μm -thick foils generate the greatest emissions for most electron energies. The emission is seen to increase roughly linearly with electron energy but shows some saturation behavior as the energy approaches 300 MeV.

Although the total emission varies linearly with electron energy, the peak intensity increases roughly as the square of the electron energy. Figure 6 shows angular distributions similar to Figure 4, except that Figure 6 was calculated with an incident electron energy of 200 MeV. Again, the intensity peaks near the $1/\gamma$ angle of 25 mradians. The doubled electron energy increases the peak x-ray flux by a factor of 4, but the total output has only doubled.

The calculations above indicated that a TR source may find application in x-ray microlithography. To see this, note that Figures 2-6 indicate that a stack of 60 $1\mu\text{m}$ -thick Be foils irradiated by 100 MeV electrons could deliver at 1m from the foils approximately 20 joules/cm² of x-rays with energies

between 1 and 2 keV per Coulomb of incident charge. If we assume that x-ray photoresists require exposures of about 100 mJ/cm^2 , then 50 seconds of a $100 \mu\text{A}$ beam of 100 MeV electrons would be sufficient. For 200 MeV electrons, the exposure time is about six seconds.

Similar calculations were performed for other low-Z materials. Foils made of boron, carbon and boron nitride are less efficient as TR sources; but these materials have large advantages in terms of material cost and toxicity and properties such as melting temperature, chemical reactivity and foil ruggedness. For boron, TR output is roughly half of the levels available from Be. And for carbon or boron nitride, the intensities are about one third of the Be levels. These differences are due largely to x-ray absorption characteristics of these materials.

Although an ideal design was not identified, the calculation's above have demonstrated that TR is a potential candidate for design of an x-ray microlithography system. Parameters such as foil thickness, number of foils, incident electron energy, desired x-ray energies, and choice of material can be chosen to match a wide range of requirements. These sources could be designed and built with well-established technology. The discussion above was intended to describe a useful approach to the design of sources of this type.

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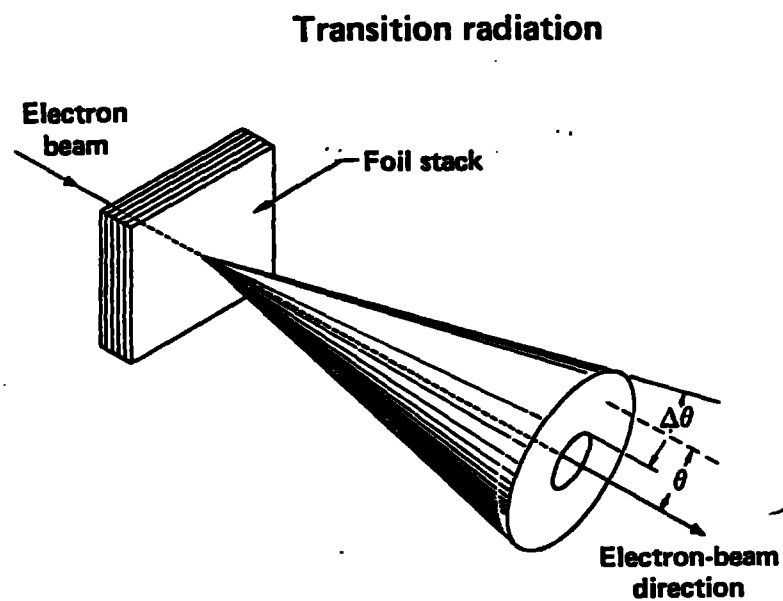


Figure 1. Schematic Diagram of Transition Radiation Source

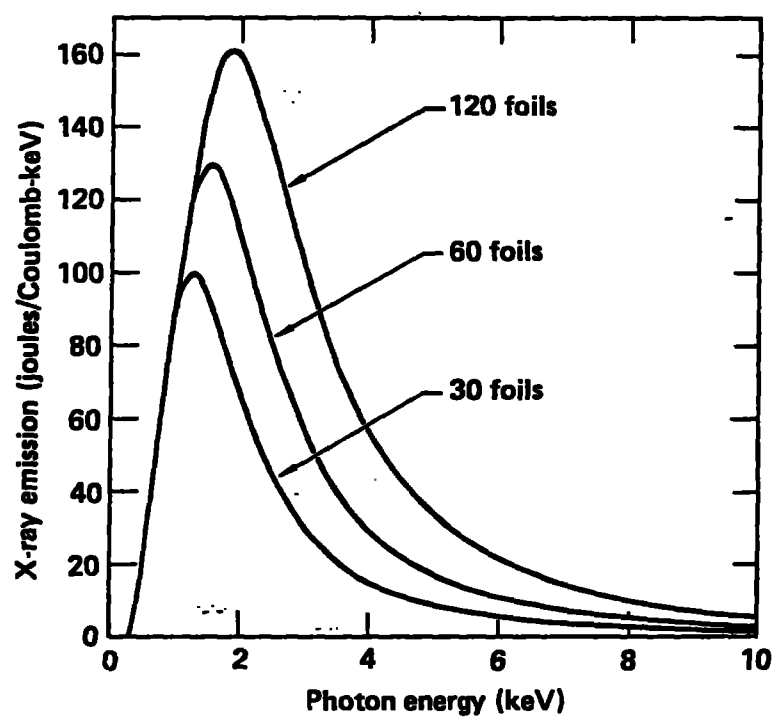


Figure 2. Transition Radiation Spectrum vs. Number of Foils in the Stack

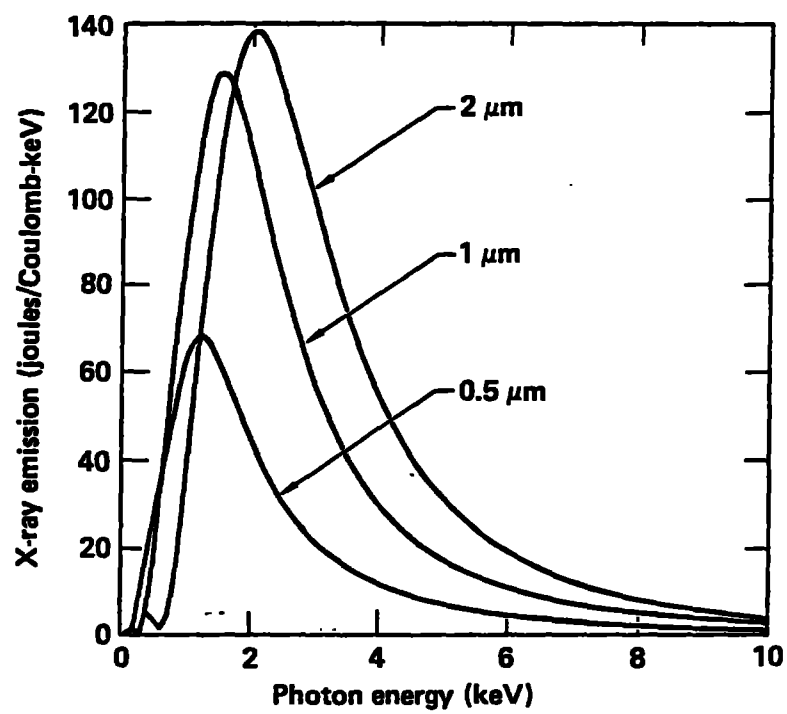


Figure 3. Transition Radiation Spectrum vs. Foil Thickness

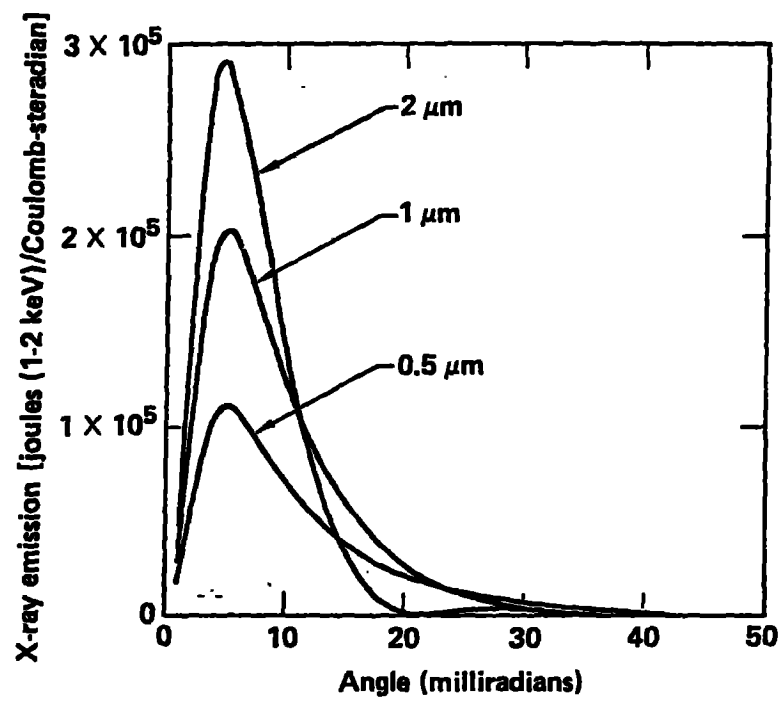


Figure 4. Transition Radiation Angular Distribution vs. Foil Thickness

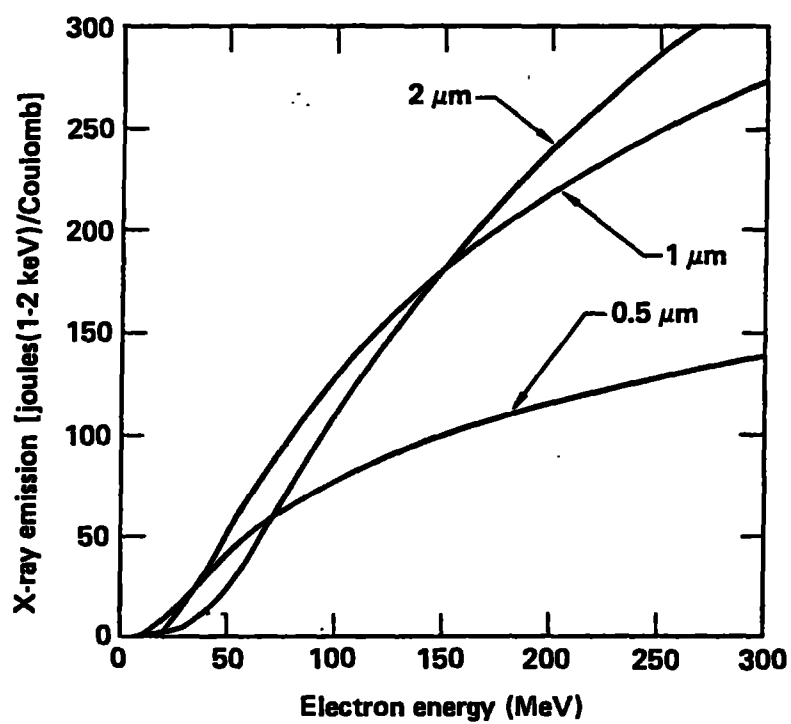


Figure 5. Integrated Transition Radiation Flux vs. Electron Energy

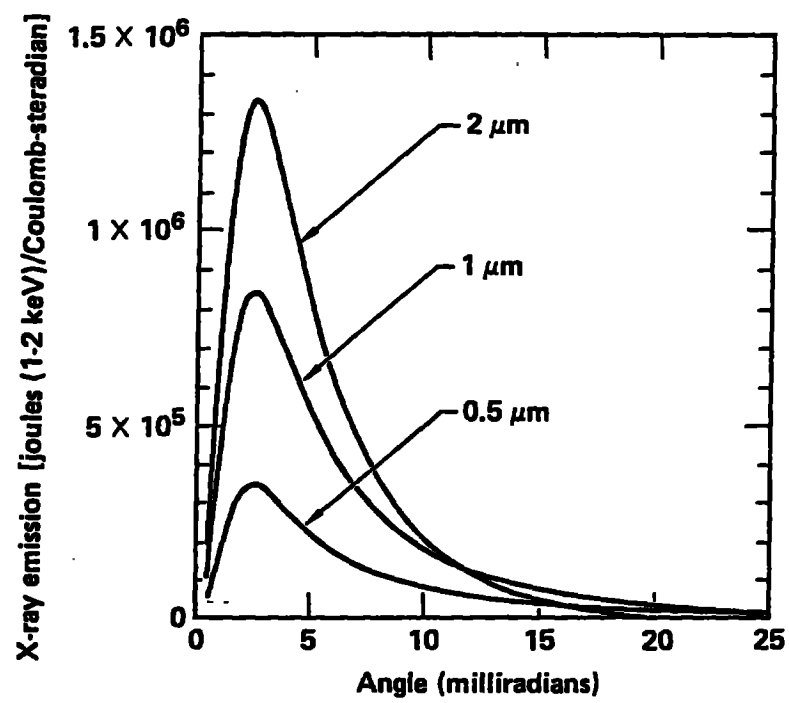


Figure 6. Transition Radiation Angular Distribution for 200 MeV Electrons.